

GTIndia2012 - 9547

ANNULAR SUPERSONIC EJECTOR DESIGN AND OPTIMIZATION

K Sathiyamoorthy

CSIR-NAL

Bangalore, Karnataka, India

Venkat S Iyengar

CSIR-NAL

Bangalore, Karnataka, India

Manjunath P

CSIR-NAL

Bangalore, Karnataka, India

ABSTRACT

An ejector is a device that entrains a secondary flow into a high speed stream that is generated by expansion of high pressure motive gas [1]. These ejectors can be broadly classified into central ejectors and annular ejectors. A large majority of applications involve central ejectors where the motive gas flow is injected along the centre of the flow passage of the secondary flow. Dutton and Carroll [2] proposed an optimization procedure for such ejectors without taking the mixed supersonic flow region into account and generated the design curves considering the constant Total temperature, Molecular weight and Specific heat ratios. However in some applications involving high temperature gases such as in ramjet/scramjet and gas turbine test facilities, an annular supersonic ejector is more appropriate where annular injection of the motive gas at the periphery of the flow passage is desired to avoid the exposure of the motive gas flow nozzle to the high temperature combustion product gases. A design and optimization procedure for an annular supersonic ejector based on the earlier approach [2] with the mixed supersonic flow region and incorporating variable Total temperature, Molecular weight and Specific heat ratios in the model has been developed based on simplified one dimensional constant area mixing model and verified using CFD software Fluent

INTRODUCTION

An ejector is a device where the momentum of a high kinetic energy fluid (primary flow) is transferred to a stagnant or a slowly moving fluid (secondary flow). Annular injection of the primary flow is a convenient alternative to other modes of injection because, by injecting the primary flow through an

annular nozzle at the internal wall of the secondary flow duct, the secondary flow passes the primary without a severe disturbance. The topic of ejector design optimization has received considerable attention. The earliest work was by Loth (1966, 1968) who developed procedures for optimizing staged ejector systems using an experimentally derived empirical model for the operation of each stage. Loth defined an optimum design as one which required the minimum primary mass flow rate for given operating pressures at the ejector inlet and outlet. Emanuel (1976) utilized a simplified constant pressure mixing analysis to predict optimum performance of single stage ejectors. He took the optimal operating point as that giving the largest exit-to-inlet compression ratio for given primary and secondary mass flow rates and inlet stagnation pressures.

Mikkelsen et al. (1976) and Hasinger (1978) both developed optimization procedures based on simplified one dimensional flow models for the problem of minimizing the primary mass flow rate for given pressure conditions (i.e., similar to the problem considered by Loth). In addition, Mikkelsen et al. obtained ejector solutions which required a minimum value of the primary stagnation pressure and also presented results typical of supersonic wind tunnel and chemical laser applications. Dutton and Carroll (1983) considered an ejector optimization problem similar to the latter in connection with natural gas vapour recovery from oil storage tanks. In this case a constant area ejector flow model was employed to find ejector designs which minimized the primary stagnation pressure required to pump given primary and secondary mass flows through a specified compression ratio.

Hewedy et al [12] have presented a computationally intensive multi dimensional approach for central ejector optimization.

Kim et al [11] carried out experiments on an annular supersonic ejector. They used a one dimensional model for theoretical prediction based on constant pressure mixing theory. They studied the effect of geometrical parameters on the performance of the ejector and did not perform any studies on developing optimal ejector designs.

Although a good deal of effort has been expended in developing procedures and solutions for optimum ejector designs, almost all of them to the authors knowledge have been developed considering constant Total temperature, Specific heat and Molecular weight ratios. An optimization procedure is developed for an annular ejector which allows the primary and secondary streams to have different stagnation temperature, molecular weight and specific heat ratios using a computationally inexpensive one dimensional model. A specialized case of ejector optimization is considered which maximizes the compression ratio for the given total pressure and entrainment ratios. A numerical procedure considering variable total temperature, specific heat and molecular weight ratios to solve the optimization problem has been developed. Using the results and analysis of Petrie and Dutton an empirical ejector pressure recovery coefficient (RE) is introduced to correct the compression ratio values. A parallel effort is done to predict the flow features and compression ratio using CFD analysis.

NOMENCLATURE

\dot{m}	Mass flow rate
P	Static pressure
P_o	Stagnation pressure
A	Cross sectional Area
M	Mach number
ρ	Density
γ	Ratio of Specific heats
R	Gas constant
\dot{m}_s/\dot{m}_p	Entrainment Ratio (ER)
P_{o_p}/P_{o_s}	Total pressure Ratio (PR)
P_m/P_{o_s}	Compression Ratio (CR)
A_p/A_m	Area Ratio (AR)
$RE = 0.8$	Pressure Recovery co-efficient

Subscripts

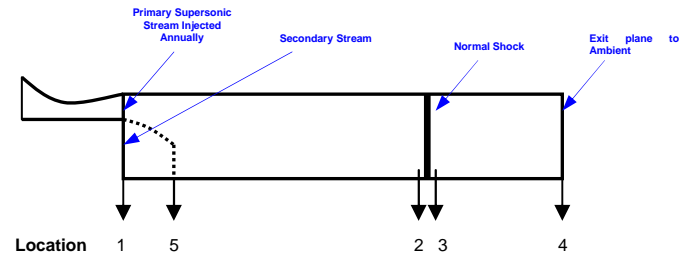
1,2,3,4 and 5	Locations in the control volume (Fig 1)
p	Primary stream
s	Secondary stream
m	Mixing duct

THEORETICAL ANALYSIS

One dimensional constant area mixing model has been chosen for optimization. Though multi dimensional models are available, they are cumbersome for optimization studies because of the large computing power requirement. The present study can give closer approximation to the optimal operating

conditions reducing the huge computational effort which is required for multidimensional models.

A schematic of the supersonic annular ejector is shown in the Fig 1. The high velocity primary stream entrains the low velocity low stagnation pressure secondary stream by viscous interaction. In this arrangement, motive or primary gas is injected annually and the secondary flow is at the centre of the duct. Both the gases mix in the constant area mixing duct and form uniform supersonic flow. Then, the supersonic flow encounters a normal shock and becomes subsonic before exiting to the ambient. The important locations are shown in the schematic. The location 1 is the inlet of supersonic primary and subsonic or sonic secondary stream. At location 2, both the streams mix uniformly and form the supersonic stream. Location 3 is the place where the flow becomes subsonic after encountering a normal shock. The flow exits to the ambient as subsonic at the location 4. The present model can predict the flow conditions at the locations 2 to 4 for the given inlet conditions at location 1. The model solves the mass, momentum and energy equations one dimensionally with usual assumptions of steady, frictionless, adiabatic flow of thermally and calorically perfect gas. The present model can accommodate the primary and secondary stream having different molecular weight, specific heat and stagnation temperature ratios.



Note: Location 5 exists in Supersonic Regime only

Fig 1 Schematic of the Annular Ejector

The ejector operation can be explained by three regimes namely 'Supersonic Regime (SR)', 'Saturated Supersonic Regime (SSR)' and 'Mixed Regime (MR)'. When primary inlet static pressure exceeds the secondary inlet static pressure in the location 1 (Fig 1), $P_{p1} > P_{s1}$, the primary stream expands against the secondary stream and forming aerodynamic throat of secondary stream at the location 5. This makes Entrainment ratio (ER) independent of Compression ratio (CR). Separate set of equation needs to be solved between the locations 1 and 5 to obtain the solution for this regime of operation. In the 'saturated supersonic regime' (SSR), the secondary inlet static pressure is greater than primary inlet static pressure, $P_{s1} > P_{p1}$, resulting in expansion of secondary stream against primary stream. Therefore the secondary stream chokes at the ejector inlet (location 1 in Fig 1). As happened in SR, in SSR 'Entrainment ratio (ER)' becomes independent of 'Compression ratio (CR)'. In SR operation $M_{s1} < 1$ and $M_{s5} = 1$

and in SSR mode of operation $M_{s1} = 1$ and location 5 does not exist. In the 'mixed regime' (MR), the compression ratio required is high enough that the secondary stream encounters area minimum neither at location 1 nor at location 5. The Entrainment ratio (ER) is therefore dependent on the Compression ratio (CR). The optimum ejector operation point can occur either in the Supersonic Regime or in the Saturated Supersonic Regime only.

OPTIMIZATION PROCEDURE

The ejector performance is controlled by the four ratios namely 'Total pressure ratio', 'Entrainment ratio', 'Compression ratio' and 'Area Ratio'. The first three ratios are the fluid dynamic controlling parameters of the ejector performance and the last one being the geometrical controlling parameter has been taken as driving parameter for optimization. The one dimensional model encompasses inputs and solution parameters as four identified ratios (Compression ratio, Entrainment ratio, Area ratio and Total pressure ratio) and primary stream Mach number (M_{p1}).

In most of the practical situations, the primary stagnation pressure and the primary mass flow capabilities are fixed by the primary source capacity. So it is better to have those constraints as the input parameters to the optimization problems. Instead of using absolute values of primary stagnation pressure and mass flow rate, they are normalized with secondary stream quantities which make the ejector optimization problems independent of ejector physical sizes.

For the given values for specific heat, molecular weight and stagnation temperature ratio of the primary and secondary streams, it is desired to determine the M_{p1} and A_{p1} / A_{m1} such that the following optimization condition is satisfied.

- For the given Total pressure ratio (P_{op} / P_{os}) and Entrainment ratio (m_s / m_p), the Compression ratio (P_m / P_{os}) is maximized.

Set of equations are written in the control volume between the locations 1 to 2, 2 to 3 and 3 to 4 (for Supersonic Regime in addition to above region 1 to 5 also has been considered) and solved iteratively satisfying the mass, momentum and energy conservation between the locations. The input parameters are 'Total pressure ratio' and 'Entrainment ratio'. The equations are solved by varying 'Area ratio' and value for 'Compression ratio' and Primary stream Mach number (M_{p1}) is obtained as the solution parameter.

The one dimensional model was found to be over predicting the compression ratio value than the CFD results because of the assumptions made. Previous experiments done by Petrie [9] and Dutton et al., [10] have shown that an empirical correction factor [RE] of around 0.8 is required to account for flow non idealities which has been used here. This value also agrees quite well with our CFD results.

$$\text{Corrected Compression Ratio } (P_m / P_{os}) = RE (P_m / P_{os})_{1-D}$$

The Area ratio corresponding to maximum value for the Compression ratio has been chosen as the optimum design point for the annular ejector. In the Fig 4, when the area ratio is increased for the given Total pressure ratio and the Entrainment ratio, the Compression ratio initially increases and after some value it starts falling forming a clear peak. The peak point is the optimized point. The solution procedure and equations for 'Saturated Supersonic Regime (SSR) operations between the location 1 and 2 is outlined in Annex A.

COMPUTATIONAL MODEL

A two-dimensional domain of the annular supersonic ejector was created and meshed using GAMBIT. To ensure grid independence, the computations were performed with three different grid sizes and a certain grid size (70000 cells) which is referred to as the baseline grid, was found to be adequate for the computations and was chosen.

With the flow characterized by High Mach number regions a density based coupled solver in FLUENT was used for this case as the coupled solver is recommended for supersonic flow. The SST k- ω model with compressibility correction was used as it is proven to exhibit better predictive capability for such flows.

Pressure inlet boundary conditions were used for the Primary inlet and mass flow inlet was used for the secondary inlet. As the diffuser exits to the atmosphere appropriate pressure was specified with a Pressure outlet boundary condition.

RESULTS AND DISCUSSION

To verify and validate the design and optimization procedure, numerical simulations were carried out for various values of Area ratio taking different combination of Total pressure and Entrainment ratios. In Fig 4, two combinations are discussed which have Total pressure and Area ratio values of (30, 0.1) and (12, 0.3) respectively. The occurrence of the different flow regions corresponding to the prescribed flow conditions was demonstrated using the CFD simulations.

For the case given in the Annex A (Fig 2), the initial mixing of the primary supersonic stream with the secondary subsonic stream leading to the near uniform mixed supersonic stream and the ensuing shock is clearly seen from the Mach number contour. Also the subsonic flow after the shock is adequately captured. The Compression ratio is estimated from the CFD results as the ratio of static pressure at the exit of the mixing duct and the total pressure at the inlet of the secondary stream.

Similar to the previous case, CFD is able to correctly capture the physics of the flow with the supersonic mixing and

shock formation followed by the subsonic region in the case 2 in Annex A (Fig 3).

The Fig 4 shows a plot where the 1-D model calculation is compared with predictions from CFD analysis for different Entrainment and Area ratios for given values of Total pressure ratio. It is clearly seen that the CFD values compare well with the 1-D model taking the pressure recovery coefficient (RE) into account. The above method can be well adopted for designing optimized annular supersonic ejector for Total pressure ratio of 5 to 100, Entrainment ratio of 0.05 to 0.75 and primary flow Mach number of 1.5 to 5 and also for the primary and secondary flows having different stagnation temperature, molecular weight and specific heat ratios

CONCLUSIONS

A technique for determining optimized supersonic annular ejector designs for a typically encountered ejector in practice has been developed considering variable specific heat, molecular weight and stagnation temperature ratios. This problem is a specialized case of ejector optimization which maximizes the ejector Compression ratio for the given the Total pressure and Entrainment ratios. Typical curves are presented for two different situations, one with a low Entrainment and high Total pressure ratio and another with a moderate Entrainment and a low Total pressure ratio. The corrected 1-D analytical results are found to have good agreement with CFD predictions as CFD computations have more physics embedded in them.

ACKNOWLEDGMENT

The authors wish to express their sincere thanks to Head Propulsion Division and the Director, NAL for all their support and encouragement.

REFERENCES

- [1] Sun D W and Eames I W (1995) "Recent developments in the design theories and application of ejectors-a review" *Journal of Institute of Energy* Vol 68 pp 65-79.
- [2] Dutton J C and Carroll B F (1986) "Optimal supersonic ejector designs" *Transactions of ASME* Vol 108 414-420.
- [3] Loth, J. L., (1966), "Theoretical Optimization of Staged Ejector Systems, Part I, " Report No. AEDC-TR-66-2, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee.
- [4] Loth, J. L., (1968), "Theoretical Optimization of Staged Ejector Systems, Part II," Report No. AEDC-TR-68-80, Arnold Engineering Development Center, Arnold Air Force Station, Tennessee
- [5] Emanuel, G., (1976), "Optimum Performance for a Single-Stage Gaseous Ejector," *AIAA Journal*, Vol. 14, No. 9, pp. 1292-1296.
- [6] Mikkelsen, C. D., Sandberg, M. R., and Addy, A. L., (1976), "Theoretical and Experimental Analysis of the Constant-Area, Supersonic-Supersonic Ejector," Report No. UILU-ENG-76-4003, Department of Mechanical and Industrial Engineering, University of Illinois at Urbana-Champaign, Urbana.
- [7] Addy, A. L., Dutton, J. C, and Mikkelsen, C. D.,(1981), "Supersonic Ejector-Diffuser Theory and Experiments," Report No. UILU-ENG-82-4001, Department of Mechanical and Industrial Engineering, University of Illinois at Urbana-Champaign, Urbana.
- [8] Hasinger, S. H., (1978), "Ejector Optimization," Report No. AFFDLTR-78-23, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio
- [9] Petrie, H. L., (1980), "An Experimental and Theoretical Investigation of Multiple Ducted Streams with a Periodic or a Steady Supersonic Driver Flow," M.S. thesis, Department of Mechanical and Industrial Engineering, University of Illinois at Urbana-Champaign, Urbana.
- [10] Dutton, J. C , Mikkelsen, C. D., and Addy, A. L., (1982), "A Theoretical and Experimental Investigation of the Constant Area, Supersonic-Supersonic Ejector," *AIAA Journal*, Vol. 20, No. 10, pp. 1392-1400.
- [11] Kim.S. and Kwon.S (2006), "Experimental determination of geometric parameters for an annular injection type supersonic ejector", *Journal of Fluid Engineering*, Volume 128, pp 1164-1171.
- [12] Hewedy N.I.I., Hamed M.H., Abou-Taleb F.Sh and Ghonim T.A, (2008), "Optimal performance and geometry of supersonic ejector", *Journal of Fluid Engineering*, Volume 130.

ANNEX A

CASE 1: COMPRESSION RATIO = 3.94, AREA RATIO =0.58

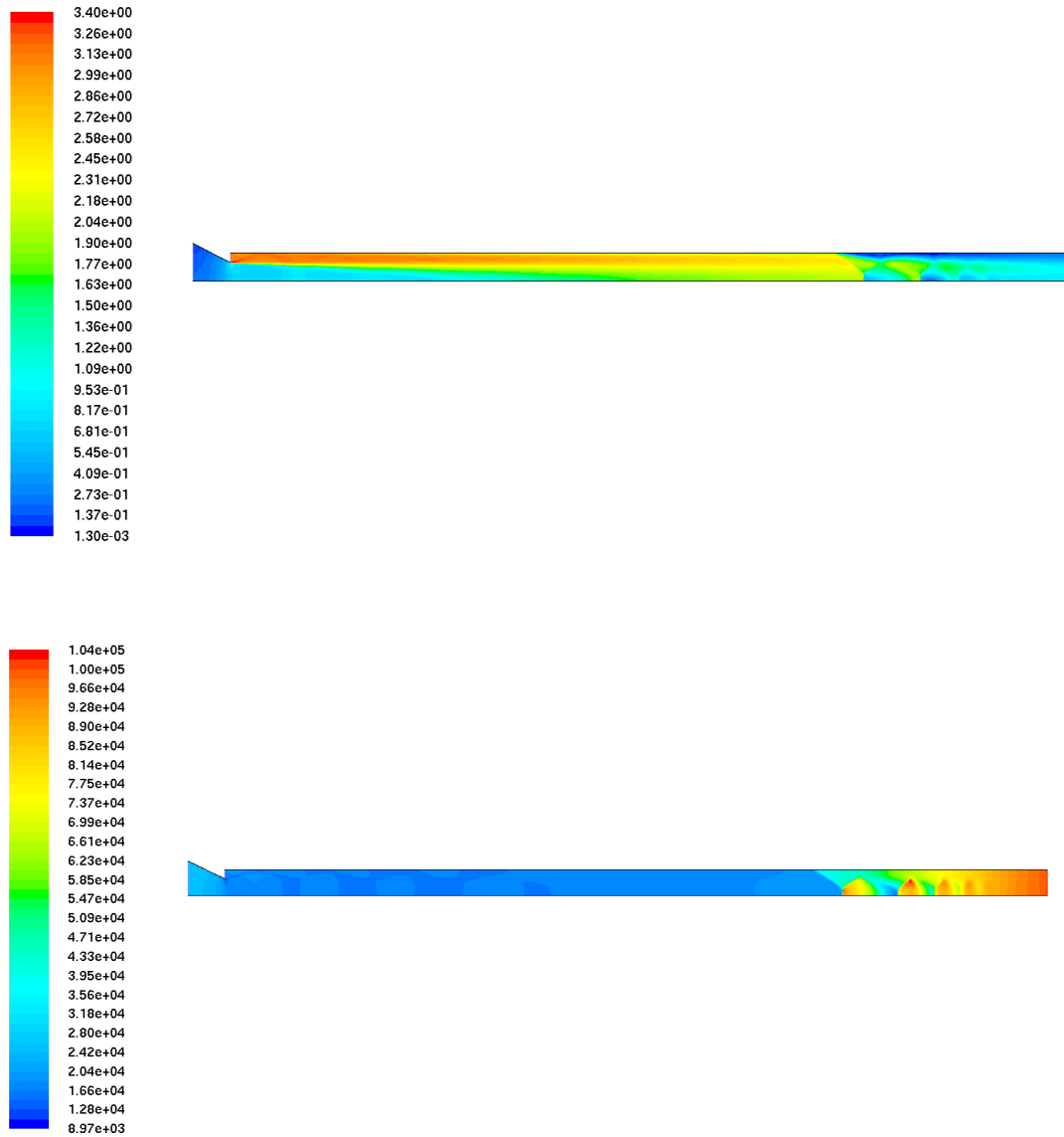


Fig 2 Mach number and Static pressure contours for the annular supersonic ejector with Total pressure ratio 30 and Entrainment ratio 0.1

CASE 2: COMPRESSION RATIO = 3.0, AREA RATIO = 0.7

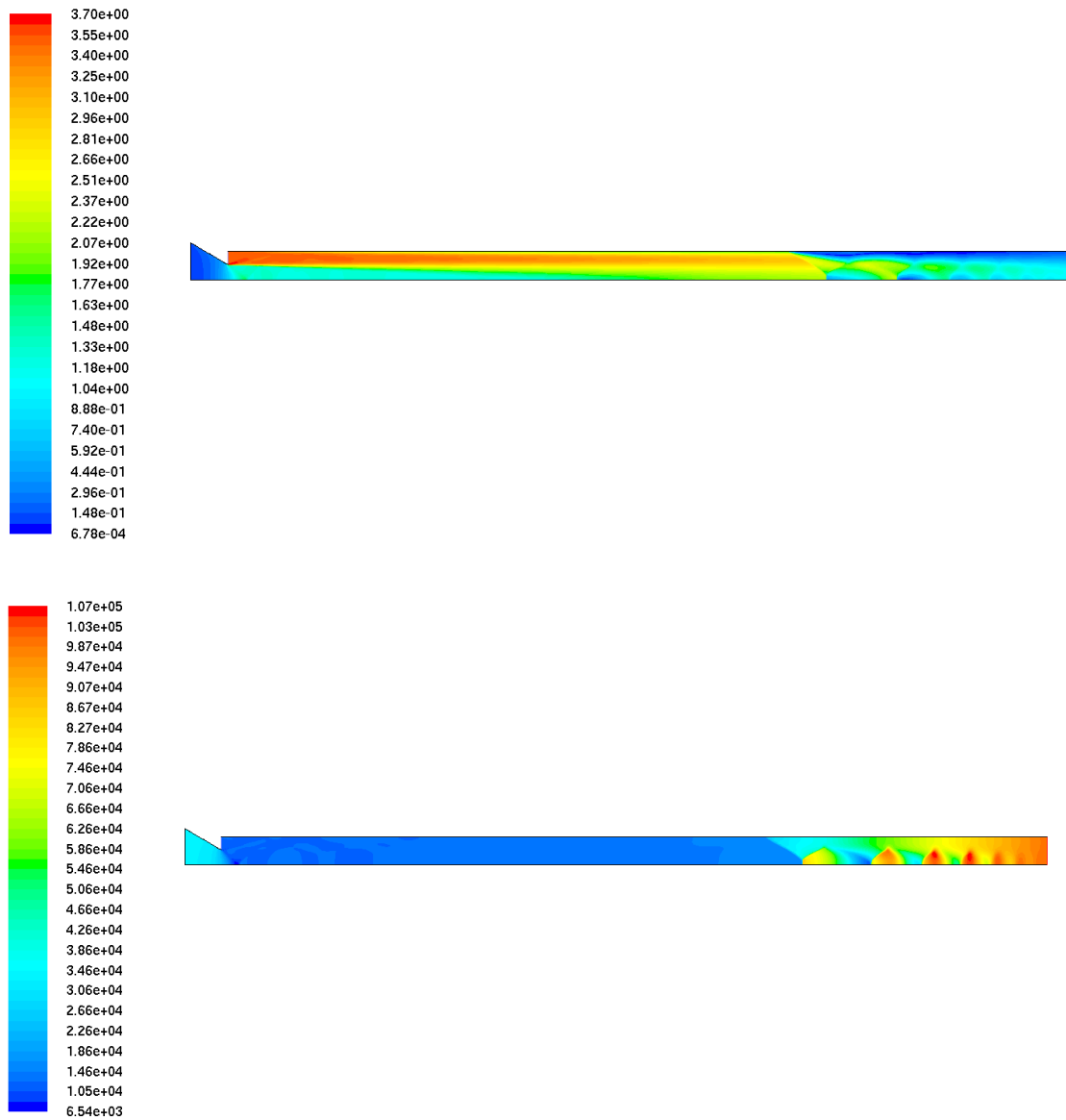


Fig 3 Mach number and Static pressure contours for the annular supersonic ejector with Total pressure ratio 30 and Entrainment ratio 0.1

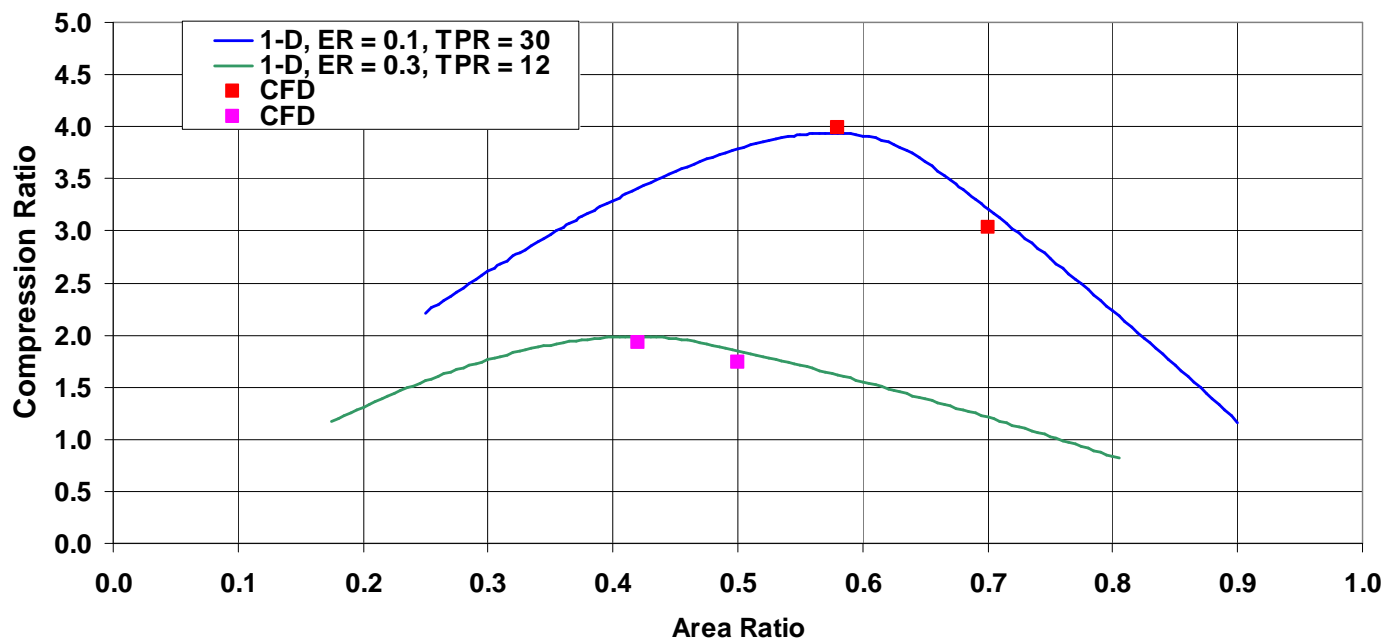


Fig 4 Comparison of analytical model with CFD predictions

ONE DIMENSIONAL GOVERNING EQUATION FOR SATURATED SUPERSONIC REGIME (SSR) OF ANNULAR EJECTOR OPERATIONS AND ITS SOLUTION METHOD

$$m_{s1} + m_{p1} = m_{m2} \text{ -----1}$$

$$P_{s1} A_{s1} (1 + \gamma_s M_{s1}^2) + P_{p1} A_{p1} (1 + \gamma_p M_{p1}^2) = P_{m2} A_{m2} (1 + \gamma_m M_{m2}^2) \text{ -----2}$$

for simplicity we introduce two parameters ψ and F which are defined as

$$\psi = \left[1 + \left(\gamma - 1 \right) \frac{M^2}{2} \right] \text{ -----3}$$

$$F = [1 + \gamma M^2] \text{ -----4}$$

by re - arrangement Equation 2 can be written as

$$\left[\frac{A_{s1}}{A_{m2}} \right] \left[\frac{F_{s1}}{\psi_{s1}^{(\gamma-1)}} \right] + \left[\frac{A_{p1}}{A_{m2}} \right] \left[\frac{F_{p1}}{\psi_{p1}^{(\gamma-1)}} \right] \left[\frac{P_{op}}{P_{os}} \right] = \left[\frac{P_{m2}}{P_{os}} \right] F_{m2} \text{ -----5}$$

It is clear from schematic that $A_s + A_p = A_m$ at all locations in the mixing duct

so $\frac{A_{s1}}{A_{m2}} = 1 - \frac{A_{p1}}{A_{m2}}$ we know that mass flow rate $m = \rho AV$ we can write

$$\frac{m_m}{m_s} = \frac{\rho_{m2} A_{m2} V_{m2}}{\rho_{s1} A_{s1} V_{s1}}$$

After some rearrangement we can write the above equation as follows

$$\frac{m_m}{m_s} = \sqrt{\frac{\gamma_m}{\gamma_s}} \sqrt{\frac{R_s}{R_m}} \left[\frac{P_{m2}}{P_{os}} \right] \left[\frac{1}{\frac{A_{s1}}{A_{m2}}} \right] \left[\frac{\psi_{m2}^{1/2}}{\psi_{s1}^{1+\gamma/2(1+\gamma)}} \right] \left[\frac{M_{m2}}{M_{s1}} \right] \left[\frac{T_{os}}{T_{om}} \right]^{1/2} \text{ -----6 similarly}$$

$$\frac{m_p}{m_s} = \sqrt{\frac{\gamma_p}{\gamma_s}} \sqrt{\frac{R_s}{R_p}} \left[\frac{P_{op}}{P_{os}} \right] \left[\frac{1}{\frac{A_{s1}}{A_{p1}}} \right] \left[\frac{\psi_{p1}^{1+\gamma/2(1+\gamma)}}{\psi_{s1}^{1+\gamma/2(1+\gamma)}} \right] \left[\frac{M_{p1}}{M_{s1}} \right] \left[\frac{T_{os}}{T_{op}} \right]^{1/2} \text{ -----7}$$

for the given values of $\left[\frac{P_{op}}{P_{os}} \right]$, $\left[\frac{m_s}{m_p} \right]$, $\left[\frac{T_{op}}{T_{os}} \right]$, $\left[\frac{\gamma_p}{\gamma_s} \right]$, $\left[\frac{R_s}{R_p} \right]$ and assumed value of

$\left[\frac{A_{p1}}{A_{m2}} \right]$ Equ - 7 can be solved for M_{p1} numerically (In SSR mode of operation $M_{s1} = 1$)

Then M_{p1} can be substituted in the Equ - 5 to get $\frac{P_{m2}}{P_{os}}$ in terms of M_{m2} and substituting Equ - 5 in Equ - 6 and solving Equ - 6 will yield supersonic Mach number for M_{m2}

Substituting M_{m2} in Equ - 5, value for $\frac{P_{m2}}{P_{os}}$ can be obtained. Using $\frac{P_{m2}}{P_{os}}$ and M_{m2} and

normal shock relation Compression Ratio of the Ejector $\frac{P_{m4}}{P_{os}}$ can be obtained